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Determinação da Respiração do Solo em uma Região do Semiárido Brasileiro

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RESUMO

Devido às recentes evidências que relacionam as mudanças climáticas ao aumento da concentração de gases do efeito estufa, é cada vez mais importante investigar as emissões provenientes das diversas atividades agrícolas. Entretanto, os valores para culturas presentes no bioma caatinga, decorrentes do uso e ocupação do solo, não são satisfatoriamente determinados, como é o caso da palma forrageira (*O. ficus-indica*), principalmente em regiões de clima semiárido, presentes na mesorregião do agreste pernambucano. Assim, objetivou-se estimar e comparar a respiração solo sob a vegetação natural (Caatinga) e sob um cultivo de palma forrageira (*O. ficus-indica*). Para tal, utilizou-se um arranjo experimental constituído de uma calota acrílica e de um medidor de dióxido de carbono. As medições foram realizadas, em ambos os casos, dentro dos limites da fazenda Santos e Silva, situada no município de São Bento do Una, na mesorregião do Agreste Meridional do estado de Pernambuco. Os ensaios permitiram classificar o comportamento da concentração de CO₂ no interior da calota em seis grupos distintos. Em ambos os casos, a respiração do solo foi estimada satisfatoriamente. Para o solo sob vegetação nativa, os valores ficaram compreendidos entre 3,7 e 14,3 $\mu\text{mol m}^{-2} \text{s}^{-1}$, com um valor médio de 7,2 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Já para o solo cultivado, os valores da respiração do solo foram estimados entre 2,5 e 11,1 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Essa diferença mostrou-se estatisticamente significativa.

Palavras-chave: Atividade agrícola, Caatinga, Gases de efeito estufa, Palma forrageira

Determination of Soil Respiration in a Brazilian Semiarid Region

ABSTRACT

The importance of examining gas emissions from various agricultural activities is growing due to recent research relating climate change to an increase in greenhouse gas concentration. However, as is the case with forage cactus (*O. ficus-indica*), the values for crops found in the caatinga biome resulting from the usage and occupation of the land are not clearly identified, primarily in semi-arid climate zones, such as those in the mesoregion of the Pernambuco agreste. Thus, this article aimed to estimate and compare soil respiration under natural vegetation (Caatinga) and a forage cactus (*O. ficus-indica*) crop. A carbon dioxide meter and an acrylic cover were used as part of this experimental setup. In both cases, the measurements were carried out within the limits of the Santos e Silva farm, located in the municipality of São Bento do Una, in the Agreste Meridional mesoregion of the state of Pernambuco. The tests produced satisfactory results, being possible to classify the behavior of CO₂ concentration inside the cap into six distinct groups. In both cases, soil respiration was satisfactorily estimated. For soil under native vegetation, the values were between 3.7 and 14.3 $\mu\text{mol m}^{-2} \text{s}^{-1}$, with an average value of 7.2. For cultivated soil, soil respiration values were estimated between 2.5 and 11.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$. This difference proved to be statistically significant.

Keywords Agricultural activities, Caatinga, Greenhouse gas, Forage cactus

Introduction

Due to recent evidence linking climate change to increased greenhouse gas concentrations, it is increasingly important to investigate emissions from various agricultural activities. In recent decades, soil respiration has received great attention as a key component of the global carbon cycle, accounting for 60–90% of total ecosystem respiration (Raich et al., 2002; Panosso et al., 2007).

Soil respiration is characterized by the release of CO₂ originating from its biological activity (roots and microorganisms). Microbial respiration is a function of the density of organisms and their metabolic condition, which depends on variations in the soil physical and chemical properties, such as temperature, porosity, water content, and pH of the medium (Ferreira et al., 2005; Gao et al., 2018).

A study conducted by the MCT (2010) between 1994 and 2002 showed that the average annual net emissions by anthropic causes, per biome, were respectively: 860.9 GgCO₂ year⁻¹ for the Amazon biome; 302.7 GgCO₂ year⁻¹ for the Cerrado biome; 37.6 GgCO₂ year⁻¹ for the Caatinga biome; 79.1 GgCO₂ year⁻¹ for the Atlantic Forest biome; and 16.2 GgCO₂ year⁻¹ for the Pantanal biome. For the years 2003-2010, the average values obtained were reduced to: 605.1 GgCO₂ year⁻¹ for the Amazon biome; 227.6 GgCO₂ year⁻¹ for the Cerrado biome; 9.8 GgCO₂ year⁻¹ for the Caatinga biome; 0.2 GgCO₂ year⁻¹ for the Atlantic Forest biome; and 9.3 GgCO₂ year⁻¹ for the Pantanal biome (MCTI 2020).

Although emissions from the conversion of natural, unmanaged formations to agriculture have decreased in the last period analyzed, the magnitude of these emissions compared to other conversions to agriculture indicates the role of native vegetation as carbon stock and the impact of the expansion of agricultural areas from the suppression of native vegetation on CO₂ emissions (Quintão et al., 2021).

However, the values for crops present in these biomes, resulting from land use and occupation, are not satisfactorily determined, especially in regions with a semi-arid climate, as is the case with the forage palm (*O. ficus-indica*) in the mesoregion of the Agreste of Pernambuco. Even though soils are well adapted to local atmospheric conditions and have been used as forage for livestock for years, only a few studies have analyzed soil respiration and its sensitivity to

the thermal characteristics of soils, especially when coupled with water characteristics.

Measurements of soil CO₂ efflux contribute to the knowledge and understanding of soil respiration in many ecosystems. However, few studies have been conducted in semiarid regions partly due to their low agricultural productivity, which has caused them to be neglected (Chen and Tian, 2005), especially in Brazil (Ribeiro et al., 2016; Ferreira et al., 2018; Maia et al., 2019).

Carbon cycle measurements of arid and semiarid ecosystems are critical to ensure the accurate representation of these ecosystems in large-scale carbon models. Carbon cycling in deserts can be particularly vulnerable to changes in climate and land use (Feng et al., 2001; Wang et al., 2004). However, the carbon dynamics of ecosystems in arid/semiarid regions and their response to environmental factors are key knowledge gaps in the global carbon balance (Cable et al., 2011).

Soil respiration can be measured using techniques based on the vertical gradient of CO₂ concentration or the above-ground atmospheric turbulence characteristics. CO₂ efflux values are commonly obtained using closed chambers through alkaline traps, where the CO₂ emitted from the soil surface is chemically trapped by an absorbing substance (NaOH or KOH). A CO₂ analyzer is also widely used (Rochette et al., 1997; Figueredo et al., 2017; Duan et al., 2019; Lima et al., 2020).

Sousa et al. (2022) analyzed the edaphic respiration of a degraded site in seven portions of different microregions of the semiarid region of Paraíba. They determined monthly soil respiration through CO₂ uptake with KOH solution, noting that the release of this gas was greater during the night than during the day, throughout the year, except in August and November, where there were no statistically significant differences between the values measured in both periods. The average annual respiration was estimated at 121.5 mgCO₂ m⁻² h⁻¹ for the daytime period and 160.7 mgCO₂ m⁻² h⁻¹ for the nighttime period.

However, there is evidence that the alkaline capture method underestimates soil respiration values, especially for high rates of CO₂ emissions (Yim et al., 2002).

Lima et al. (2020) measured soil respiration emitted by Caatinga vegetation and a degraded pasture in the semiarid region of Pernambuco to verify the effect of land use changes

on soil respiration. To measure CO₂, they used the infrared gas analyzer method over nine months. They concluded that soil respiration showed a clear seasonal variation, with the highest values occurring in the rainy season, and that soil respiration was significantly higher in Caatinga (8.0-ton ha⁻¹ year⁻¹ of C) than in degraded pastures (3.7-ton ha⁻¹ year⁻¹ of C).

Several devices can measure soil respiration using this methodology; however, it is not possible to integrate the CO₂ flux for a long time, and a large number of experiments are required to determine representative values for the 24 hours of the day, besides the high cost of the available devices (Ferreira et al., 2005).

Thus, the objective was to estimate soil respiration through an experimental setup consisting of an acrylic cap and a carbon dioxide meter in natural soil (Caatinga) and in soil cultivated with forage palm (*O. ficus-indica*) located in the semiarid region of Pernambuco.

Material and Methods

Study site and climate

The data necessary for implementing this study were obtained in soil under a culture of forage palm (*O. ficus-indica*) and another under native vegetation (Caatinga), both within the limits of the Santos e Silva farm, located in the municipality of São Bento do Una in the mesoregion of the Southern Agreste in the state of Pernambuco, 199 km from the capital of Pernambuco (Figure 1). The location's geographical coordinates are 8° 36' 37" S latitude, 36° 21' 45" W longitude, and 621 m altitude.

The semiarid climate predominates in the locality, with hot and dry summers, and the rainy season extends from April to June. The region's climate is classified as BSh, according to the Köppen-Geiger classification. The average annual precipitation is below 300 mm, and the natural vegetation is composed of hyperxerophilic Caatinga (Embrapa, 2006).

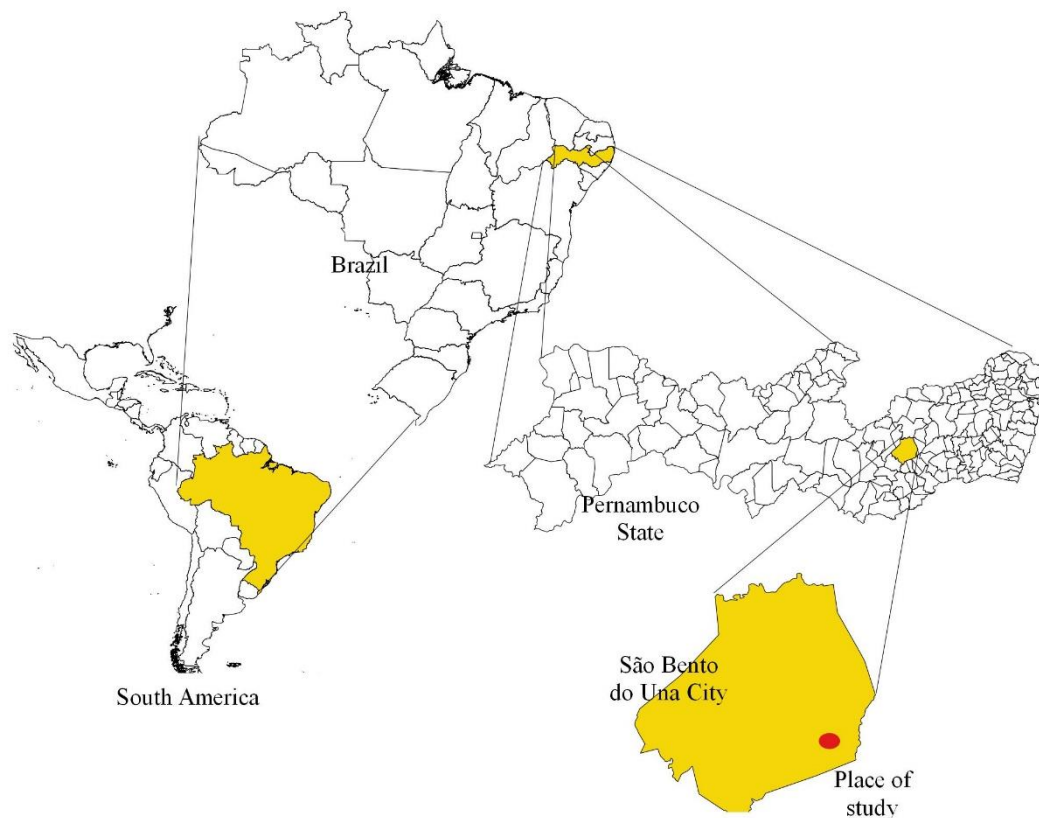


Figure 1: Study area location

According to residents, some of whom are over 90 years old, the caatinga vegetation present

in the study area has never been deforested. The shrub vegetation most frequently found is

composed of Jurema preta (*Mimosa hostilis Benth.*), Jurema branca (*Mimosa hostilis*), and, more rarely, the Umbuzeiro (*Spondias tuberosa*). Among the cactaceans present, the most noteworthy are the foxtail (*Harrisia adscendens*), the Facheiro (*Pilosocereus catingicola*), the Mandacaru (*Cereus jamacaru*), and the Xiquexique (*Pilosocereus gounellei*). Figure 2 shows a portion of the soil plot under Caatinga.

In the portion where the native vegetation was removed and used for farming, the forage palm

(*O. ficus-indica*) has been cultivated for at least 40 years, the soil is turned by machinery, and the planting is done manually. Organic fertilization with manure happens twice during the crop cycle: once before planting and once a year after the first. In both cases, about three tons of ha^{-1} is used. Part of the cultivated soil portion with the forage palm can be seen in Figure 3.



Figure 2: Caatinga portion under study



Figure 3: Parcel of cultivated soil under study and surrounded by native vegetation

Physical characteristics of local soils

First, soil samples were collected at various site points from both parcels, producing a representative mesh. These samples were taken to the laboratory to determine soil particle size fractions (sand, silt, and clay), porosity (ϕ), density (ρ), and saturated bulk moisture (θ_s). A complete description of the methodology for obtaining these data can be seen in Soares et al. (2020).

Table 1 shows the established values. The soil was texturally classified as sandy loam in both cases. The bulk densities of the soils cultivated with Caatinga, and forage palms were 1.69 g cm^{-3}

and 1.43 g cm^{-3} , respectively. The lower value of soil density with native vegetation was expected due to the preparation necessary for planting the palm. Another factor influencing soil compaction in the Caatinga region is its slope, which increases surface runoff.

It was also possible to notice a significant increase (about 27%) in soil porosity in the cultivated area (46.04%) compared to the values obtained for the portion with native soil (36.23%). This difference is due to the soil management and, consequently, the respective bulk density values.

Table 1: Physical characteristics of the studied soils

Soil	Clay (%)	Silt (%)	Sand (%)	ρ (g cm^{-3})	ϕ (%)	θ_s $\text{cm}^3\text{cm}^{-3}$
Natural	10.63 ± 3.2	17.24 ± 1.5	72.13 ± 2.6	1.69 ± 0.04	36.23 ± 3.7	0.344
Cultivated	15.10 ± 2.7	16.71 ± 1.2	68.19 ± 3.1	1.43 ± 0.05	46.04 ± 3.2	0.437

Determination of soil respiration

For CO_2 flux measurements, we used the methodology described by Norman et al. (1992) and adapted by Davidson et al. (2002). For this, an experimental apparatus composed of an acrylic cap and a carbon dioxide analyzer was made (Figure 4).



Figure 4: Measurement of CO_2 efflux in the soil

The acrylic cap has a maximum internal height (h) of 0.178 m and a diameter (d) of 0.38 m. With these measurements, it was possible to establish both the ground area covered by the cap ($A=0.113 \text{ m}^2$) and its internal volume ($V_{\text{cap}} = 0.013 \text{ m}^3$ or 13 l), by equations 1 and 2, respectively:

$$A = \frac{\pi d^2}{4} \quad (1)$$

$$V_{\text{cap}} = \frac{\pi h^2}{3} \left(3 \left(\frac{d}{2} \right) - h \right) \quad (2)$$

At the cap's edges, there is a flat one-centimeter ledge (Figure 5), which, in addition to improving ground support, minimizes air leakage from its interior, where there is an increase in CO_2 concentration.



Figure 5: Detail of the cap base

The CO_2 concentration and air temperature inside the cap were determined using a CRIFFER model CO-6 Plus carbon dioxide meter with a data logger, which can present an error of up to 3% for CO_2 values and up to 0.6°C for temperature. The dimensions of this meter are $160 \times 60 \times 40 \text{ mm}$, with a volume (V_{sensor}) of 0.384 l.

A few moments after placing the experimental apparatus on the ground, an increase in the CO₂ concentration inside the cap can be noticed. From a linear fit of these data, it is possible to determine the variation of CO₂ concentration in time ($\frac{dCO_2}{dt}$, $\mu\text{mol s}^{-1}$).

Soil respiration (R_s , $\mu\text{mol m}^{-2}\text{s}^{-1}$) was determined by Equation 3:

$$R_s = \frac{dCO_2}{dt} \cdot \frac{PV}{RTA} \quad (3)$$

V is the volume of air inside the cap (l), A is the ground area covered by the cap (m²), R is the gas constant (0.08206 l atm mol⁻¹ K⁻¹), T is the air temperature inside the cap (K), and P is the atmospheric pressure (atm), which was determined as a function of the location's altitude (Alt), Equation 4: The air volume inside the cap was determined by the difference between the cap and sensor volumes (Equation 5).

$$P_{\text{Atm}} = 101.3 \left(\frac{288 - 0.0065 \text{Alt}}{288} \right)^{5.257} \quad (4)$$

$$V = V_{\text{cap}} - V_{\text{sensor}} \quad (5)$$

Data Analysis

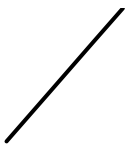
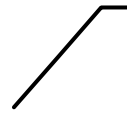
Linear fits of the CO₂ concentration data over time and statistical analyses to determine if statistically significant differences were performed with R software (R Development Core Team, 2019).

Results and discussion

From the methodology adopted, it was possible to determine, inside the cap, the variation of CO₂ concentration over time and thus estimate soil respiration satisfactorily.

Behavior varied identified in the growth measurements of CO₂ concentrations and was classified into six groups according to their appearance. Table 2 summarizes these characteristics, including their conduct, a graphical representation of each group, and the percentage of cases observed during this study. These perturbations in CO₂ diffusion gradients can be corrected with curve fitting (Davidson et al., 2002).

Table 2: Grouping of the ways of increasing CO₂ concentration inside the cap

Group	A	B	C	D	E	F
Conduct	Increasing Linear	Plateau plus increasing linear	Decreasing Linear then Increasing	Plateau plus increasing linear plus plateau	Increasing Linear plus plateau	Linear decreasing then increasing with steepening slope
Graphic aspect						
Percentage of cases	29.41%	35.29%	23.55%	3.92%	1.96%	3.92%

In the first group, the concentration curve inside the cap presents a linearly increasing behavior. The temperature inside the cap had a range of about 20 °C with a minimum value of 23 °C and a maximum of 42.7 °C. Approximately 30% of the experiments presented this behavior.

Figure 6 shows the graph of CO₂ concentration by time from a test belonging to this group. In measurements with these characteristics, the increase in CO₂ concentration is perceptible to

the sensor almost instantaneously. Therefore, CO₂ production by the soil is enough to raise the concentration quickly.

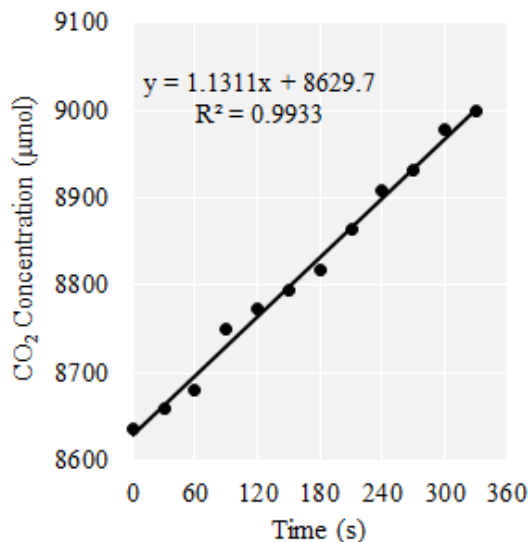


Figure 6: Linear behavior of the increasing CO₂ concentration inside the cap.

Figure 7 shows a typical representative of an element belonging to the second group (group B). An initial plateau characterizes the elements of this group, and then a linear increase in CO₂ concentration values inside the cap.

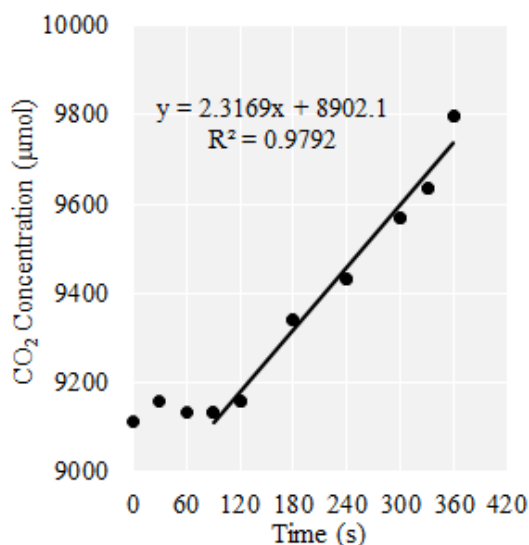


Figure 7: Presence of a plateau before the linear behavior of the increasing CO₂ concentration inside the cap.

Temperatures inside the cap in the experiments with this characteristic presented a temperature range of 17 °C, with a minimum value of 25.9 °C and a maximum of 42.5 °C. Approximately 35% of the experiments presented this behavior.

It is assumed that in the samples of this group, more than the CO₂ produced by the soil was needed to raise the concentration inside the cap

quickly. Only after a few minutes was there a noticeable increase in the sensor used.

Group C combines the experiments that showed decreasing and increasing CO₂ concentrations inside the cap. This behavior was observed in 23.5% of the cases, with amplitude of approximately 16 °C, a minimum temperature of 27.6 °C, and a maximum of 43.4 °C. Figure 8 shows an example of this group.

The overwhelming majority of the essays, about 90%, exhibit one of these characteristics, falling into one of these three groups. The other behaviors can be considered exceptions. In all elements of these three groups, the coefficient of determination (R^2) was greater than 0.94, indicating a perfect representation of the data by the linear curve.

During the measurements of CO₂ concentration from the soil under the acrylic cap, about 4% of the experiments showed two plateaus in the determined values (Figure 9): the first, at the beginning of the experiment, when it was not yet possible to determine the variation of the concentration, and the second plateau, at the end of the experiment, when the air is saturated with carbon dioxide. The determination of the CO₂ rate occurred between these two levels.

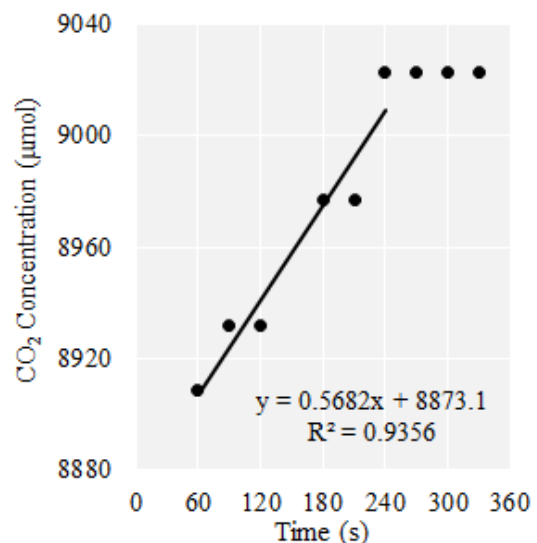


Figure 8: Decreasing and increasing behavior of the CO₂ concentration inside the cap.

The air temperatures inside the cap for the tests with this characteristic were between 27.3 °C and 34.3 °C.

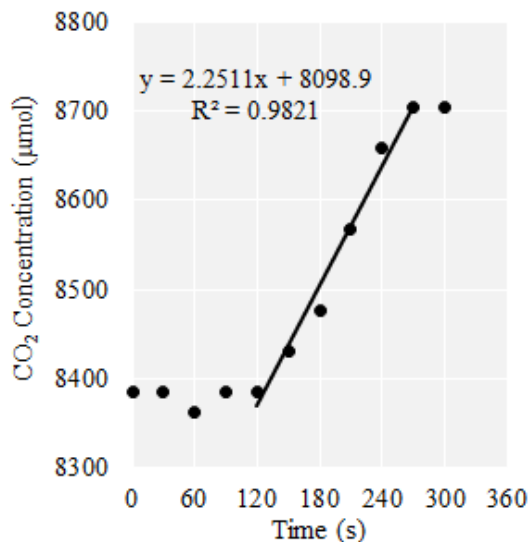


Figure 9: Determination of the CO₂ concentration inside the cap between two plateaus.

In a few cases (about 2%), it was possible to notice the presence of a plateau after the linear behavior of the CO₂ concentration, as shown in Figure 10. The experiments presenting this behavior were grouped in Group E.

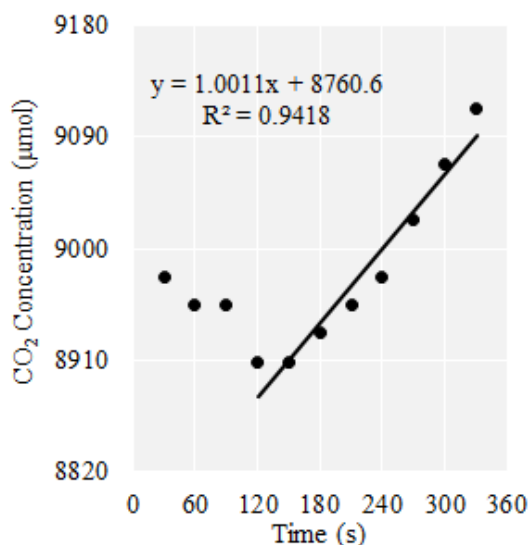


Figure 10: Presence of a plateau after the linear behavior of the increasing CO₂ concentration inside the cap.

A behavior similar to Group C was observed in approximately 4% of the experiments. These trials were referred to as Group F and showed a linear downward behavior, a linear increase, and a steeper slope on the straight line after a few moments.

Figure 11 shows the graph of a representative test for this group. In all these cases,

the first slope was used for the soil respiration calculations, disregarding the second slope.

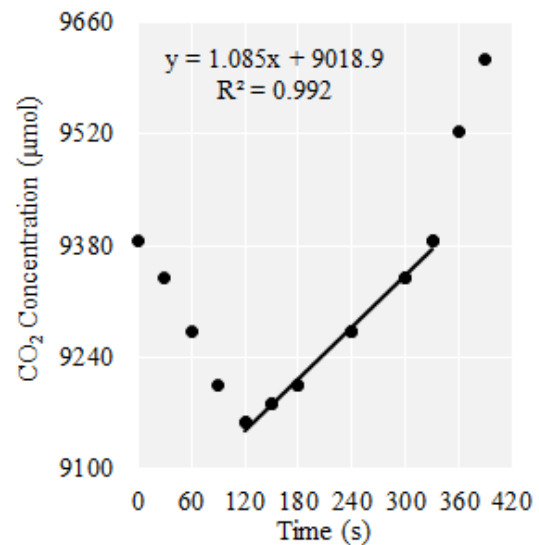


Figure 11: Decreasing and increasing behavior with two slopes of CO₂ concentration inside the cap.

Besides the cases in these six groups, there were also times when the curve produced by varying the CO₂ concentration showed a decreasing linear behavior. These cases only occurred in about 2% of the experiments and when the tests were performed during a drizzle. The CO₂ concentration variation was not determined in these cases, and the trials were neglected.

Soil respiration

From the determination of the variation in CO₂ concentration, it was possible to satisfactorily estimate the soil respiration values using equation 3, as seen in Figure 12.

Soil respiration under Caatinga showed minimum and maximum values of 3.7 and 14.3 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively, and a mean of 7.2 $\mu\text{mol m}^{-2} \text{s}^{-1}$. About 50% of the measurements showed values between 5 and 10 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

The estimated values for soil respiration under the forage palm presented a very divergent behavior from those found for the natural soil. About 75% of the values found for this soil had lower values than the average value of the soil under Caatinga. The minimum and maximum values found for this soil were 2.5 and 11.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively, not considering the outliers found for this soil.

The estimated values for soil respiration under native vegetation and oil palm cultivation

presented statistically different values when evaluated by the ANOVA test at 5%.

The higher values found for the native vegetation are probably due to the greater presence of microorganisms in the decomposing vegetation. The low respiratory activity observed in the soil under cultivation may be due to lower microbial population diversity, given the characteristics adopted in crop management.

The density of the soil under study decreased from 1.69 g cm^{-3} (native soil) to 1.43 g cm^{-3} (cultivated soil), negatively altering the activity of its microorganisms and the processes involved in the decomposition of organic matter and nutrient cycling and thus reducing CO_2 diffusion rates (Silva et al., 2011).

This difference was already expected and corroborated the results found in the literature. For example, Valentin et al. (2015) compared CO_2 production in forest and degraded areas and observed that the average annual soil respiration in the forest was higher than in degraded areas. Lima et al. (2020) also noticed that soil respiration was significantly higher in Caatinga ($8.0 \text{ ton ha}^{-1} \text{ year}^{-1}$ of C) than in degraded pasture ($3.7 \text{ ton ha}^{-1} \text{ year}^{-1}$ of C), in the municipality of São João-PE. When analyzing different areas in the semiarid region of Paraíba, Correia et al. (2015) noticed that the more conserved the ecosystem, the greater the CO_2 release.

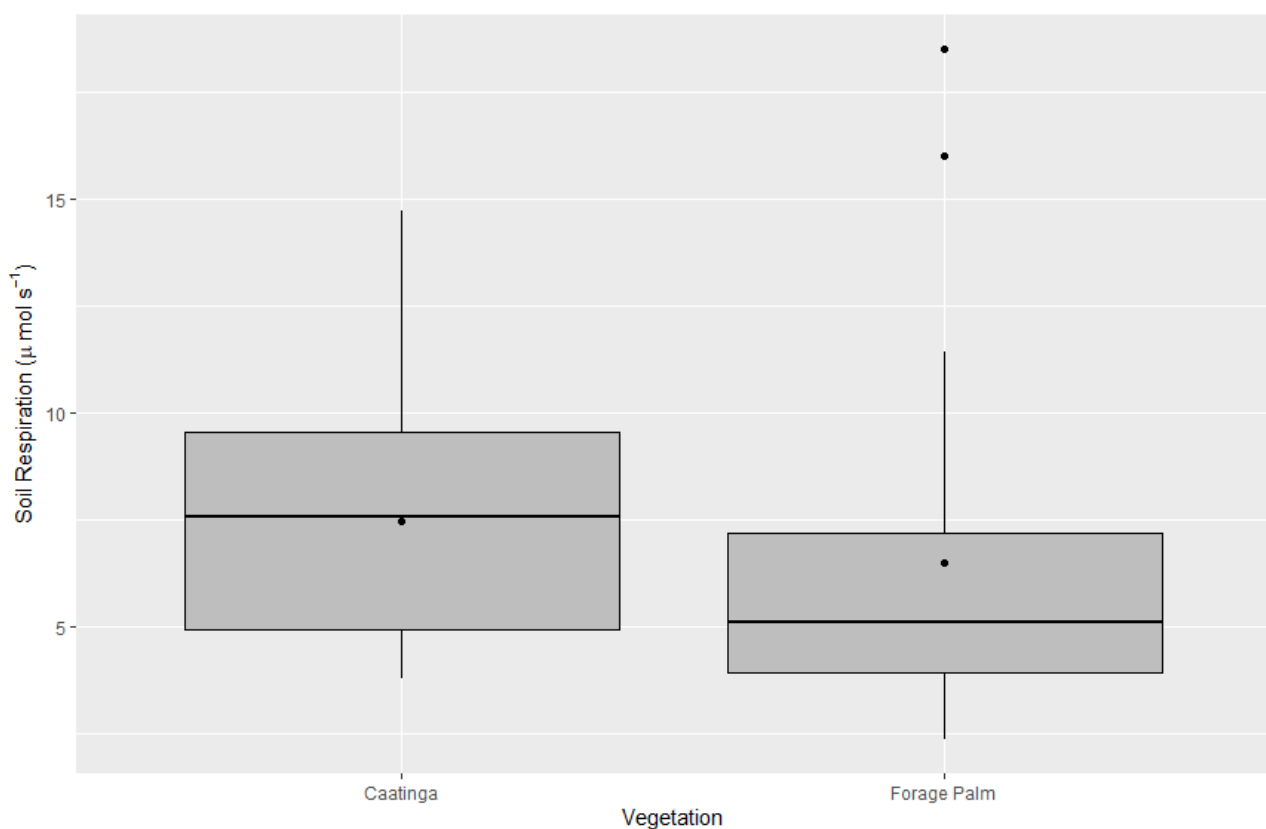


Figure 12: Soil respiration box plot for soil under native vegetation (Caatinga) and cultivation (Palm).

Another possibility for the lower respiration of the cultivated soil compared to the natural soil is in each soil's percentage of clay. While 10.63% of the natural soil is composed of clay, in cultivated soil, this value increases to 15.10%. Depending on the type of clay, it may have a higher cation exchange capacity, exposing the

native organic carbon to binding decomposition (Nguye and Marschner, 2014).

Balogh et al. (2011) observed that the soil water content that optimizes soil respiration depends significantly and positively on the soil's clay content, especially for the surface layer, from 0 to 10 cm. When determining soil respiration in experiments with clay addition in sandy soils,

Raias and Marschner (2020) concluded that clay content can significantly alter the soil's ion exchange capacity, reducing respiration.

Conclusion

Determining the variation of CO₂ concentration inside the cap by the evaluated methodology proved satisfactory.

Six distinct behaviors were observed for the CO₂ concentration. In all cases, the linear fit was sufficient to mitigate the perturbations presented in the diffusion gradient.

A statistically significant difference was observed between the estimated values for soil respiration determined at the sites containing natural vegetation and palm cultivation.

No dependence could be seen between the estimated values for soil respiration and the internal temperature of the acrylic cap used in the experiment.

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